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Application of Aquarius to River Basin Planning: Factors Influencing Water Consumption in the Gunnison River Basin

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Introduction

In the state of Colorado, where population has increased by over 30% in the last ten years (http://quickfacts.census.gov), the evaluation of the allocation of water resources has become increasingly important.. As the state's population continues to grow, competing demands will place further pressure on Colorado's scarce water resources. According to the Colorado Division of Water Resources, Colorado will need an additional 632,000 acre-feet of water by the year 2030 for municipal and industrial (M&I) use alone, which amounts to an increase of approximately 40 percent over what is being used today. The addition of 2.8 million residents statewide by the year 2030 is clearly a driving force behind this increased demand, but it is not the only reason. In addition to the increase in M&I water demands, there has been increased pressure on

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water resources in all sectors, including agricultural, recreational, environmental, and industrial (http://water.state.co.us).

In order to meet this increased demand for water and allow for the economically efficient allocation of water across all sectors, policy makers must first identify the factors influencing water consumption throughout the state. The identification of these factors can help to 1) estimate future annual water demand in different areas of the state; 2) create and implement effective water conservation programs; 3) identify where institutional reforms might allow for a more economically efficient water allocation and 4) guide public entities in decisions concerning water development projects.

In order to facilitate comprehensive river basin planning, the USDA Forest Service (USFS), Rocky Mountain Research Station has recently developed Aquarius, a state of the art computer model devoted to the temporal and spatial allocation of water among competing uses in a river basin. The model is driven by an economic efficiency operational criterion requiring the reallocation of stream flows until the net marginal return, or marginal productivity, in all water uses is equal. When resources are allocated efficiently, no further change in water use from one sector to another can increase overall utility. Maximization occurs when the return on the last unit of water is same for all water use sectors. In essence, this is the equimarginal principle as applied to water resources.

An economic efficiency criterion was adopted for determining water allocation because economic demands play a key role in water allocation decisions, and because economic value estimates for nontraditional water uses such as instream and lake recreation have greater accessibility (USFS 2006). The model is unique in that it aims to

incorporate water demand functions based on economic data rather than on simple per-capita use estimations.

The model's input data is divided into both physical and economic data for each river basin in Colorado. The physical data include information associated with the dimensions and operational characteristics of the system components, such as maximum reservoir capacity, percent of return flow from an off-stream demand area, and power plant efficiency. The economic data consist mainly of the demand functions of the various water uses competing for water. The purpose of this research is to develop river basin demand estimates for input into Aquarius.

Prior to the development of Aquarius, water demand estimates used for regional planning purposes have traditionally been based on per-capita use, found by dividing total consumption or demand by the total population of the study area. This approach to water resources planning does not result in efficient water resource allocation nor does it result in effective conservation policy because it does not identify those variables influencing water use.

Objectives

This research stems from the need to understand the factors influencing water use and to evaluate the allocation of water resources across competing water uses. The purpose of this research is to aid in the application of Aquarius. Specifically, this research will develop an aggregate river basin demand model for the different water uses in the Gunnison River Basin. The resulting demand model will be used for input into Aquarius.

Literature Review

Several studies have been conducted in the area of water demand estimation. Water demand models generally fit into one of two broad categories. The first approach employs mathematical programming optimization techniques. Studies are performed to identify a number of feasible water consumption measures together with alternative designs, inputs and operating conditions and the associated costs of each. This information is incorporated into a mathematical programming model, with the objective function formulated to maximize profits or minimize costs. The demand function is then approximated by solving the model across different water prices and recording the amount of water required or used at each price. This approach is more appropriate for macro analyses (BBC Research 2001) and is usually applied to producer's water use in industries such as agriculture.

The second category is statistical, making inferences from actual observations on quantities consumed, and their relationship to corresponding data on water prices, incomes, climatic variables, the effects of conservation programs and other influences. Typically, an abstract demand function is formulated, which asserts a hypothesized connection between water consumption and the various factors that exert influence. Parameters of demand equations in this approach are inferred via statistical inference, usually through multiple regression techniques. Currently, almost all modeling approaches documented in the literature are based to some degree on regression analysis. This research will follow the same general approach. The remainder of this literature review focuses primarily on the different methodologies associated with this type of demand study.

Water demand studies generally differ in the type of data used (Pint 1999). Hansen and Narayanan (1981), for example, used time series data on aggregate water consumption for a single community. Howe and Lineweaver (1967) used cross-sectional data on aggregate water consumption in 21 U.S. cities. Several studies, including Billings and Agthe (1980), Billings (1982), Billings and Day (1983) and Martin et al. (1984) have employed pooled cross-section and time series or panel data on household water use in Arizona. For the purpose of studying the effects of price on household water consumption, detailed household billing data seems most appropriate, and ideally it should be panel data rather than pooled time series and cross-section data (Pint 1999).

The vast majority of available literature focuses on techniques and issues in forecasting residential water demand at the micro-economic (household) level. This may be because the residential sector is the easiest sector for which to obtain empirical data, as it typically comprises the majority of the utility's total demand, or because water demand in the residential sector is the most susceptible to seasonal influences that provide interesting challenges for forecasters. Residential demand studies have typically employed causal structural models, which are by far the most common type of models used to forecast water demand for major metropolitan water purveyors today (BBC Research 2001). Causal structure models use regression analysis to construct equation(s) that depend on the ability of the analyst to determine the relationship between water consumption and a variety of potential explanatory variables.

The economic literature broadly supports the standard economic theory that the household demand function for water is downward sloping in price. However, most studies of water price elasticity, such as Howe and Lineweaver (1967), Foster and Beattie

(1979), Epsey et. al (1997) and Dalhuisen (2003), have generally found water to be relatively price inelastic, indicating that at current levels, price does not significantly influence water demand. Weather and climate variables have also been found to explain a large percentage of the seasonal variation in water demand (Pint 1999). Both price and climate variables will have different degrees of influence for different sectors. For example, in Colorado price is generally not a factor among agricultural users as most water users in the agricultural sector are members of mutual associations and do not pay a per-unit price for water. Agricultural users are also more susceptible to changes in climate than most industrial users.

In addition to price, a number of other explanatory variables have been used to explain variation in residential water demand. The most commonly used is household income (or mean aggregate income). Income is expected to have a positive, significant income on water demand, and this has nearly always been the case (Foster and Beattie, 1979; Nieswiadomy, 1992; Michelson et al., 1999). Another variable related to homeowner characteristics that has been employed in previous studies is age of the homeowner (Billings and Day 1989). Other household or neighborhood characteristics that have been used in estimating residential demand include house size, lawn size (Hewitt, 1998), number of bathrooms (Chiacoine et al., 1986), number of residents (Chiacoine et al., 1986), and house age (Nieswiadomy, 1992). Dummy variables have also been used to capture location and seasonality effects (Billings and Agathe, 1998) and the effects of non-price conservation programs (Nieswiadomy, 1992; Michelson et al., 1999).

Demand model estimation for commercial, industrial and other users employ a somewhat different set of explanatory variables. There is a great diversity of purpose for which water is used in the commercial and industrial sectors. Commercial and industrial demand has therefore been somewhat difficult to estimate (Renzetti, 1992; Schneider and Whitlach, 1991). Another difficulty is that much of the relevant information is not readily available for individual establishments or is aggregated into political or census-designated boundaries.

This study differs from most previous research in that it attempts to estimate total water demand across all sectors. The goal is to identify the factors influencing total demand for a specific river basin. Rather than being carried out for a particular sector, this study is conducted at a macro-level and therefore lends itself to several differences in methodology from the studies discussed above.

To begin with, this study will not use price as a variable in the estimation of water demand. The model developed does not therefore represent traditional demand in the economic sense of price responsiveness. Price is not included in the regression analysis for several reasons: 1) Water pricing does not reflect true market price because water agencies are often legally and politically constrained in their pricing policies. Single-purpose water districts are not usually allowed to earn profits, and the profits and price structures of privately owned water agencies are typically set by regulatory agencies. As a result, when marginal costs are above average costs, most water agencies are precluded from setting the water price at marginal cost because their profits would be too high; 2) The price elasticity of water has been found to be very inelastic, which indicates that price does not influence water use; and 3) this study is conducted at the macro-level

across all use sectors. Water prices and pricing methods tend to vary greatly across the different use sectors. For example, agricultural users in the study area are typically not charged a volumetric fee per unit of water use; this is because most irrigation water in the state is allocated via mutual share ditch companies rather than irrigation districts. Further differences in methodology will be discussed in the Methods section below.

Study Area

The Gunnison River Basin encompasses 8,000 square miles on the western slope of the Rocky Mountains in west-central Colorado. The Gunnison River extends from the continental divide to Grand Junction, Colorado, where it joins the Colorado River. The Basin is comprised of seven major water districts, based on major tributaries including Tomchi Creek, North Fork of the Gunnison, Lower Uncompahgre, Lower Gunnison, East River Basin, Upper Gunnison, and the Upper Uncompahgre.

The basin is comprised of portions of seven counties including Delta, Gunnison, Hinsdale, Mesa, Montrose, Ouray, and Saguache. Between 1990 and 2000, the population in this region increased by 35 percent and now accounts for 1.8 percent of the state's total population. Population in the region is expected to increase substantially in the next ten years, placing further pressure on competing uses for water resources (CWCB 2006).

Traditional water rights administration on the Gunnison River is expected to become more controversial as different users begin to compete for scarce water resources. Recovery flows for endangered fish and reserved rights for the Black Canyon National Park are expected to change the status quo. Agriculture is the dominant water

use in the region and tributaries are primarily controlled internally by senior agricultural water rights.

Under the Endangered Species Act, four Colorado River native fish species are listed as endangered on the Gunnison River: Colorado pike minnow, humpback chub, bonytail chub, and razorback sucker. Causes for the decline of these species include alteration of stream flows by water projects, introduction of non-native species and efforts to remove the native fish from the system in the past.

There are currently 195 instream flow segments totaling approximately 1219 stream miles in this basin. These decreed water rights are held by the Colorado Water Conservation Board to protect the natural environment to a reasonable degree. The decreed flow for each of these instream flow segments is based on the level of flow necessary to maintain the "water-dependent natural environment" (CWCB 2006)

The major water development feature in the basin is the Aspinall Unit of the Colorado River Storage Project, consisting of Blue Mesa, Crystal and Morrow Point Reservoirs. The three reservoirs store approximately 1.1 million acre-feet. Interstate compacts limit development of the basin yield. Future development will be limited by the Aspinall Unit Section 7 Endangered Species Act Consultation (CWCB 2006).

Data and Methods

In order to determine total water demand, water use-data was regressed against socioeconomic data and watershed characteristics. This study is a panel data, macro-economic study utilizing watershed-level data for the seven sub-basins within the Gunnison River Basin.

Water-use data was collected for each of the Gunnison's sub-basins (as defined by the Colorado Division of Water Resources) across each water-use sector for water years 2000 through 2004. Data was collected for 20 different use sectors or categories including total trans-mountain and trans-basin outflow, storage, irrigation, municipal, industrial, recreation, fishery, domestic/household (self-supplied), stock and augmentation, evaporation, power generation, snow making and other miscellaneous uses. This data was obtained from the Colorado Division of Water Resources. The number and variety of the water users included in the study exemplifies the potential for conflict among competing users as increased demand begins to place further pressure on scarce water supplies.

The socio-economic and agricultural data used in the study was obtained at the County-level for Delta, Hinsdale, Gunnison, Mesa, Montrose, Ouray and Saguache Counties from the U.S. Census and the National Agricultural Statistics Service (NASS). Annual rainfall data was obtained from the Natural Resources Conservation Service (NRCS) and the Colorado State Climate Center. Employment statistics were obtained through the Colorado Department of Labor. All county-level data was converted to the sub-basin level through the use of GIS technology and data obtained through the Colorado Decision Support Systems (CDSS). Through the use of GIS, portions of each county were allocated to their respective sub-basins. This allocation allowed the formulation of sub-basin level population and other socio-economic estimates. Initially, 2000-2004 data was collected for population, percent of population under five years of age, percent of population over 25 with a bachelor's degree, median household income, density, number of households, number of people employed, owner/renter ratio, total

cropland, total irrigated acres, median farm income, total number of cattle, and annual precipitation.

Population data for 2000 was obtained at the county level from the U.S. Census. Population data for 2001-2004 was estimated based on population growth in each County from the last census in 1990 to 2000. This method was also used for the percent of population under five years of age, percent of population over 25 with a bachelor's degree, number of households, and owner/renter ratio data. Density (persons per square mile) for 2000-2004 was simply determined based on population projections and total land area. Median household income projections were obtained directly through the U.S. census. Annual employment statistics were obtained for 2000-2004 directly from the Colorado Department of Labor.

Agricultural data was more difficult to obtain at the county-level. The data available for years other than 2002 (year of the last Agricultural Census) included total irrigated and non-irrigated acres of cropland by crop type, average farm income, and number of cattle. Crop data was aggregated in order to obtain total irrigated acres and total cropland at the county-level for each year. Farm income data was unavailable for 2004.

Annual precipitation data was obtained for the gauging stations within the seven counties in the Gunnison River Basin. Percent of average annual precipitation (1971-2000) for each station was obtained from the Colorado State University Colorado Climate Center for water years 2000-2004. The average annual precipitation for each station was obtained from the NRCS. Total annual rainfall (inches) was then calculated.

As the economic model was developed, specification of the exogenous variables was based on economic theory and institutional knowledge, as well as availability of data. Consistent with the "modern" econometric method, model specification followed the "test down" approach. As a first step to model specification, data was evaluated for basic descriptive statistics and correlation between variables (Refer to Table X). All data was compiled using Microsoft Excel and imported into Limdep 7.0 for regression analysis.

As noted, water use data was originally collected for the seven sub-basins across 20 different use sectors or categories. However, several of these categories are dependent on unique sub-basin characteristics and are not necessarily a function of specific variables represented in the model. For example, Crested Butte Ski Resort is located in Sub-basin 59. Annually, an average of 175 af was used for snowmaking in this district between 2000 and 2004. Snowmaking is not an identified use in any of the other water districts, and the fact that Crested Butte ski resort is located within District 59 would not be predicted by the typical parameters included in a water demand model. For this reason, observations for snowmaking were not included in the specification of the demand model. Similar rationale was used for the recreation and power generation use sectors. Demand for these particular uses will be added into total demand after the model has been estimated and before the resulting demand estimates are input into Aquarius.

Several of the use sectors identified by the Colorado Division of Water Resources are not relevant to the Gunnison River Basin. There has been no documented consumption for the commercial, geothermal, minimum stream flow, wildlife, or recharges water use categories. Theses sectors were also not included in the specification

of the demand model. The use sectors or categories that were used in initial model development include transmountain and transbasin outflow, storage, irrigation, municipal, industrial, fishery, self-supplied domestic, stock and augmentation, evaporation, and miscellaneous uses.

Due to the limited number of sub-basins within the sample and the relatively short time period of analysis, the data was pooled across the different water use sectors for each year. Each sector was represented by a dummy variable in the economic model. The pooling of data results in higher degrees of freedom associated with the model, allowing for a sufficient number of regressors to be represented in the model. Final model specification pooled data for the years 2000 through 2004 across nine different water use categories and seven sub-basins, for a total of 315 observations. The following model was developed:

$$W = \beta_0 + \beta_i X_{it} + \beta_j D_s X_{jt} + \Gamma_u D_s + \mu$$

Where:

W = total water use,

X_{it} = vector of socio-economic and watershed characteristics, where *i* denotes the cross section identifier and *t* is the time identifier,

$D_s X_j$ = vector of sector characteristics "turned on" for the appropriate use sector,

$\Gamma_u D_s$ = intercept shifting dummy variable for each use sector, and

μ = random error term.

The dummy variables $\Gamma_u D_s$ represent the change from the mean of the intercept coefficient associated with each use sector. The dummy interaction term $\beta_j D_s X_j$ allows for sector-specific characteristics to be included in the appropriate sector equation. For

example, the agricultural sector may significantly differ from the municipal sector in terms of factors influencing total use. Economic theory dictates that the number of irrigated acres within a sub-basin would greatly influence agricultural water use. On the other hand, it is more unlikely that the number of irrigated acres within a particular sub-basin would influence domestic water consumption. Thus, the dummy interaction term allows for certain characteristics to be associated only with specific sectors.

The data collected includes several zero observations for water use and is therefore known as a limited dependent variable or censored sample. A censored sample is a sample in which information on the regressand is only available for some observations. For example, water use for fisheries was documented for only four of the seven sub-basins. The remaining three sub-basins reported zero water use for this purpose. In order to account for the censored data, a Tobit model was used for the estimation of water use.

The Tobit model is an extension of the probit model and was originally developed by James Tobin, the Nobel laureate economist. With a Tobit model, the analyst is not only interested in whether or not a particular water use sector is consuming water within a given sub-basin, as with a probit model, but is also concerned with how much water is actually being consumed. The Tobit model divides the water use data into two groups, one consisting of n_1 observations about which there is information on the regressors as well as the regressand. The second group consists of n_2 observations about which there is information only on the regressors but not on the regressand. In the context of water use modeling, the n_1 observations values for the dependent variable, W, are observed only when water use is actually occurring. Thus, a censored version of the variable is

observed. The regression cannot be estimated using only the n_1 observations because the resulting OLS estimates will be biased as well as inconsistent. The Tobit model takes both the n_1 and n_2 into account using the method of maximum likelihood (ML). The resulting ML estimates are consistent, asymptotically normal, and efficient (Gujarati 2003).

Specifically, the Tobit model is expressed as:

$W_i^* = \beta_1 + \beta_2 X_{it} + u_i$

$W_i = W_i^*$ if $W_i^* > 0$

$W_i = 0$ if otherwise, where $u \sim (0, \sigma^2)$.

With a Tobit model, a change in an independent variable will have two different impacts, 1) it will change the amount of water used among those sectors already using water, and 2) it may induce water use where none existed before. The water use model detailed above was run as a Tobit model using Limdep 7.0. Regression results, the marginal effects of the independent continuous variables, and the discrete changes associated with the dummy variables used in the model are presented in the results section below. The coefficient for the Inverse Mills Ratio is not included in the Limdep output because Limdep uses the method of single maximum likelihood to estimate the Tobit model.

The t-statistics and p-values of the individual parameter estimates were evaluated for significance throughout the model estimation process. A likelihood ratio (LR) test was performed on the final model to test overall significance. The LR test used the log likelihood functions for the restricted (coefficients restricted to zero) and the unrestricted regressions (λ_R and λ_{UR}) to determine the Chi-square statistic, where:

$\chi^2 = 2 * (\lambda_{UR} - \lambda_R)$

Results

Summary statistics and the correlation table for the socioeconomic variables are presented in Appendix III-A. Due to the high degree of correlation between number of households and population, and number of households and population density, number of households was not used as a socioeconomic variable in the final model. Final Tobit regression results are presented in Table III-1 below.

The Tobit model was estimated with the following variables:

W = water use

POP = population of water district

PERUND5 = percent of total population under 5 years old

PERBACH = percent of total population over the age of 25 with a bachelor's degree

INC = median household income

DENSITY = population density

PRECIP = annual precipitation (inches)

EMPLOY = number of people employed

AREA = land area (sq. miles)

D3 = irrigation water use dummy variable

D5 = industrial water use dummy variable

D7 = water use for fishery dummy variable

D8 = self-supplied domestic water use dummy variable

D9 = water use for stock and augmentation dummy variable

D10 = other water use dummy variable

IRRDUM = dummy interaction term for irrigation water use and irrigated acres

INCDUM = dummy interaction term for irrigation water use and farm income

CATDUM = dummy interaction term for irrigation water use and number of cattle

TABLE III-1: Tobit Regression Analysis

Variable	Coefficient	Standard Error	P-Value
Constant	6,485,615.8300	1,242,908.5000	0.0001
POP	23.2452	5.2712	0.0001
PERUND5	-73,558,816.0200	13,867,802.0000	0.0001
PERBACH	-13,381,479.0800	2,350,878.2000	0.0001
INC	26.7140	7.3393	0.0003
DENSITY	-69,669.5526	13,090.7430	0.0001
PRECIP	2,475.8514	8,339.1532	0.7665
EMPLOY	-11.3346	6.2767	0.0709
AREA	-153.8118	41.8253	0.0002
D3	-83,263.5867	69,319.7280	0.2297
D5	-183,958.5896	40,335.8000	0.0001
D7	-66,456.7077	32,215.5660	0.0391
D8	-133,376.3463	35,468.5270	0.0002
D9	-100,165.6690	33,383.2550	0.0027
D10	-26,024.1063	31,565.9950	0.4097
IRRDUM	11.5561	3.1176	0.0002
INCDUM	-35.4466	7.6665	0.0001
CATDUM	-7.8313	3.4232	0.0222

Log-likelihood function = - 2226.863

As Table III-1 indicates, the intercept shifting dummy variables for industrial, fishery, domestic and stock and augmentation water uses are significantly different than municipal water use, which is represented by the constant in the final model. The intercept shifting dummy variables for irrigation and other water uses are not significantly different from municipal water use. The high p-value associated with the irrigation dummy variable is more than likely a result of the fact that irrigation water use is by far the dominant water use in each water district. The large volume of water used for this purpose dominates the relatively small effect of municipal water use.

As described in the previous section, a likelihood ratio test was performed on the final model, based on the log likelihood functions for the restricted and unrestricted regressions. The null hypothesis of the likelihood ratio test is that the coefficients on each of the variables are equal to zero. The calculated Chi-square statistic is 151.156, which is greater than 35.72, the chi-square statistic for 17 degrees of freedom at the 0.05 significance level. Thus, the null hypothesis is rejected, and the regression is found to be significant.

The β estimates above represent the marginal impact of the independent variables on the latent variable, W_i^*, or the propensity of different sectors to consume water. However, because Wi* is unobserved, the marginal effects of the latent variable are of secondary interest. The marginal effects of W_i were therefore calculated such that:

$$\partial E(W \mid \partial X)/\partial X = \beta * \text{Prob}[Wi^* > 0], \text{ or}$$

$$\partial E(W \mid \partial X)/\partial X = \varphi(\beta' X/\sigma)\beta$$

Again, the calculation of the marginal effects assumes censoring at zero and normally distributed disturbances. The marginal effects of the continuous variables used in the final model are presented in Table III-2 below. These represent the marginal effects of the observed Wi for actual water consumed by consumers and non-consumers, where the probability that Wi* > 0 is .5207. These effects are noticeably smaller as they are multiplied by the proportion of non-zero observations (Greene 2003).

TABLE III-2. Marginal Effects of Continuous Variables.

Variable	Coefficient	Standard Error	P-Value	Mean of X
Constant	3376801.5700	641112.4200	0.0001	
POP	12.1029	2.7415	0.0001	33055.3880
PERUND5	-38299142.5900	7093671.9000	0.0001	0.0557
PERBACH	-6967202.6130	1204669.1000	0.0001	0.1986
INC	13.9089	3.7581	0.0002	36387.3060
DENSITY	-36274.1582	6799.4465	0.0001	12.9914
PRECIP	1289.0771	4343.5784	0.7666	10.2392
EMPLOY	-5.9015	3.2685	0.0710	15878.0520
AREA	-80.0837	21.7382	0.0002	2420.6649
IRRDUM	6.0168	1.6376	0.0002	4087.9047
INCDUM	-18.4557	4.1392	0.0001	-354.6538
CATDUM	-4.0775	1.7872	0.0225	3506.8817

As presented in Table III-2, water use was found to increase with population and median household income of the water district. Agricultural water use is also shown to increase with the number of irrigated acres, as indicated by the positive sign on the dummy interaction for irrigated acres and agricultural water use. The p-values associated with these coefficients indicate that they are all significant at well below the 5% level. The positive relationships between water use and the independent variables above are consistent with basic economic theory. As shown in Table III-2, the sign on the coefficient for annual precipitation is also positive. However, the p-value of 0.7666 that is associated with the precipitation coefficient indicates that it is generally not significantly different from zero. Upon further evaluation, this lack of significance is also consistent with economic theory. The mean annual precipitation in the Gunnison River Basin is approximately 10.24 inches, a level that is often technically classified as dessert conditions. Thus, a small increase in annual precipitation will likely not influence total water use. This is particularly true for irrigation water use, which dominates total water use in each water district.

The inverse relationship between water use and population density indicates that as people begin living closer together, they require less water. This relationship is easily explained by the fact that increased population density is likely correlated with a decreased number of irrigated acres, both for domestic landscaping and agricultural production. Together, these two types of water use constitute a majority of total water use in the basin. Thus, as population density increases, water use is expected to decline. This indicates that infill development may be relatively water conserving in a physical sense.

The model also indicates that total water use decreases as the percent of children under 5, percent of population with a bachelor's degree, density, employment, and total land area increase. With the exception of employment, the coefficients on these variables are also significant at well below the 5% level. These relationships are also generally consistent with economic theory. To begin with, an inverse relationship between percent of total population under the age of 5 may be explained by the fact that young children use less water than adults. Second, a higher percentage of people with a bachelor's degree may indicate that people with a higher level of education are more likely to be aware of the benefits of water conservation. The relationship between employment and water use may mean people use less water while working than they do at home, contributing to an overall decrease in total water use.

Finally, the inverse relationship between total land area and water use at first blush does not seem to make sense. However, in the Gunnison River Basin, the more populated basins are generally smaller in total land area. These explanations for the

relationships identified in the final model represent simple hypotheses on the factors that influence water use in the Gunnison River Basin. These relationships warrant further research.

Model results show that water used for irrigation increases with the number of irrigated acres, as expected. Factors found to influence decreases in agricultural water use include increased farm income and increased number of cattle. These relationships are also in need of further research specific to the Gunnison River Basin.

The marginal effects associated with the dummy variables represent discrete changes rather than percent increases in their relative frequencies. The discrete changes associated with the intercept-shifting dummy variables are presented in Table III-3 below. These changes represent only those sectors with observed water use, and not the non-zero observations.

Table III-3. Discrete Changes in Dummy Variables.

Variable	Coefficient	Standard Error	P-Value
D3	-83,263.5867	69,319.7280	0.2297
D5	-183,958.5896	40,335.8000	0.0001
D7	-66,456.7077	32,215.5660	0.0391
D8	-133,376.3463	35,468.5270	0.0002
D9	-100,165.6690	33,383.2550	0.0027
D10	-26,024.1063	31,565.9950	0.4097

Summary and Conclusions

Results indicate that the model performed relatively well. However, model results are limited by the data available. Unfortunately, it was difficult to obtain socioeconomic data for years other than census years. Much of the socioeconomic data was extrapolated for years 2001-2004 based on differences in the 1990 and 2000 census.

Agricultural data for each year was also limited to irrigated acres, number of cattle and farm income.

Further model limitations may result from the translation of county data to the water district level. As explained in the methodology section, data was translated based on the percent of each county making up the specific water district. Problems with this method may result where population is not evenly distributed across water districts. The translation of county level data to the water district level may be further refined through the use of GIS technology.

Results indicate that the final model is reasonably robust and capable of providing necessary data for limited economic analysis. The model is unique in that it incorporates all water users within a district rather than focusing on one specific sector. A second unique factor is that the model is based on river basin boundaries rather than demand as dictated by political boundaries. Comprehensive river basin planning is an important factor in the efficient allocation of water resources. This final model will serve as valuable input into USFS Aquarius.

Model results are specific to the Gunnison River Basin and generally cannot be applied elsewhere. The model is not intended for use as a forecasting tool and results should not be extrapolated far out of sample.

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Appendix III-A: Summary Statistics for Initial Data Collected

TABLE III-1-A: Summary Statistics

Variable	Mean	Std.Dev.	Minimum	Maximum	Cases
POP	33055	37303	3750	124505	252
HOUSES	13138	14573	1579	48694	252
INC	$ 36,387.31	$ 3,837.59	$ 29,189.32	$ 45,427.16	252
ORR	2.5436	0.5941	1.4070	3.5389	252
DENSITY	12.9914	10.9651	2.9524	37.4114	252
CATTLE	31562	17422	7320	71677	252
FARMINC	$ (3,191.88)	$ 5,453.01	$(12,282.81)	$ 12,050.97	252
AREA	2420.6649	913.6060	541.3537	3328.0000	252
PRECIP	10.2392	2.9321	6.3467	17.0962	252
IRR	36791.1427	18423.3999	7008.6615	69092.7442	252
EMPLOY	15878	18508	2151	62890	252
PERUND5	0.0557	0.0072	0.0461	0.0675	252
PERBACH	0.1986	0.0558	0.1232	0.2696	252

TABLE III-2-A: Correlation Table for Socioeconomic Variables

	POP	HOUSES	INC	ORR	DENSITY	CATTLE
POP	1					
HOUSES	1.0000	1				
INC	-0.0224	-0.0222	1			
ORR	0.3251	0.3219	0.2466	1		
DENSITY	0.9527	0.9520	0.0824	0.5030	1	
CATTLE	0.6584	0.6561	-0.3241	0.4166	0.6976	1
FARMINC	-0.1284	-0.1301	-0.4200	-0.3381	-0.2530	-0.3619
AREA	0.4421	0.4452	-0.6950	-0.3263	0.2265	0.3897
PRECIP	-0.5184	-0.5179	0.6645	-0.1114	-0.4923	-0.6965
IRR	0.3929	0.3894	-0.7626	0.1746	0.3401	0.7265
EMPLOY	0.9960	0.9959	-0.0082	0.2690	0.9474	0.6369
PERUND5	0.5727	0.5686	-0.2509	0.4637	0.6697	0.8259
PERBACH	-0.6024	-0.5995	0.3154	-0.4602	-0.7121	-0.8411

	FARMINC	AREA	PRECIP	IRR	EMPLOY	PERUND5
FARMINC	1					
AREA	0.1690	1				
PRECIP	0.0515	-0.6237	1			
IRR	0.2009	0.5799	-0.7468	1		
EMPLOY	-0.1139	0.4306	-0.5118	0.3727	1	
PERUND5	-0.3035	0.1524	-0.7189	0.6410	0.5710	1
PERBACH	0.3084	-0.2177	0.7662	-0.6366	-0.5969	-0.9761

Conclusion to Thesis

The Gunnison River basin perhaps represents some of the most pristine areas of Colorado's high country. Although development pressures are not expected to be as intense in the Gunnison River basin as in many other parts of the state, there are many significant water issues in this basin that will require management in the future.

This thesis provides a brief look into some of the key water management issues facing the future management of water resources in the Gunnison River Basin. These issues include 1) population pressures and increased demand across competing users, 2) water quality, 3) water quantity, and 4) implications for endangered species.

The three papers in this series respectively evaluate the impact of selenium remediation alternatives at the farm-level; the regional impacts of a government cost share program for selenium remediation as compared to a no-action scenario; and the different factors influencing water demand across all users in the basin.

Specifically, the first two papers in this series evaluate the farm level and regional economic impacts associated with selenium remediation in the Gunnison River Basin. The goal of this research is to identify remediation strategies that achieve sufficient reduction of selenium for protecting endangered fish while minimizing impacts to agricultural production and the local economy. The studies focus on increasing irrigation efficiency as a primary method of selenium remediation.

The first study applied a non-linear programming model to farms within the Uncompahgre Valley Water Users Authority (UVWUA). Model results indicate that considerable potential exists for reducing salinity and selenium loading into the

Gunnison and other rivers by improving irrigation system performance. With conversion to more efficient irrigation systems, the total amount of water diverted for application and the total amount of return flow both decrease substantially. As a result, salt and selenium loading into the river is also substantially reduced. Study results estimate the maximum potential total salt load reductions associated with the conversion from gravity-type irrigation systems to gated pipe, sprinkler, and drip systems, respectively. The largest total selenium reduction results from conversion from gravity to drip irrigation systems.

Increased irrigation efficiency was found to have implications for levels of instream flow across the different stages of the model. Due to the nature and location of the return flows, increased efficiency was found to result in higher levels of stream flow. Although not significant in an economic sense, increased stream flow in various locations may have important ecological implications for fish habitat and relative selenium concentrations. Further impacts associated with the adoption of new irrigation technology included decreased penalty fees for the use of water in excess of four-acre feet per acre and a shift in cropping patterns towards additional production of alfalfa, pasture, and corn.

Although considerable potential exists for substantial reductions in total salt and selenium loads, model results indicate that irrigators on the Uncompahgre River have very little incentive to increase irrigation efficiency. To begin with, baseline model results showed no impact to yield as a result of salinity. Until concentrations of salinity begin to approach crop threshold levels, no incentive exists to irrigate more efficiently.

In addition, model results indicate that current profits per acre average approximately $159.56. Based on capital investment costs and reduced penalty fees alone, the implementation of more efficient technology substantially reduces this figure across each conversion scenario. Per-acre profits associated with conversion to gated pipe, sprinkler, and drip irrigation technologies are $125.75, $115.63, and $99.84. This respectively amounts to a $2.36, $2.91, and $3.94 million decrease in total agricultural profits in the region.

The first study in this series captures only the on-farm costs associated with the adoption of more efficient irrigation technology, assuming that individual farmers would bear the full cost of implementation. As noted, farmers in the region have no immediate economic incentive to invest in new technology. This problem represents a classic market failure in that the social costs of current agricultural production are much higher than those incurred by the producer. Further, the private benefits of improved water quality for any given producer do not even begin to approach the costs associated with remediation. Thus, government cost-share programs and/or other policy-based incentives may be necessary to prevent further water quality degradation and future loss in agricultural productivity in the region.

In order to fully evaluate the costs and benefits of the implementation of a government cost-share program for selenium remediation, the economic impacts to the local economy must be taken into account. The objective of the second paper in this series was therefore to identify the regional impacts associated with a government cost-share program for each of the three irrigation technology adoption scenarios evaluated in the first study. In order to fully evaluate the benefits and costs associated

with alternative selenium remediation strategies on the Uncompahgre River, the study also evaluated the costs of taking "no action" (no remediation), as a basis for comparison. This stage of the analysis estimated the impact of a percent reduction in irrigated acreage that may result from a further increase in soil salinity.

Impact results show relatively large regional benefits associated with the government purchase of more efficient irrigation technology for farms within the UVWUA. The total effects to output across the three adoption scenarios are $4,947,919, $6,386,164, and $8,628,136, for the GRGP, GRSP, and GRDR scenarios. This is compared to a cost of $2,258,316, $2,914,756, and $3,938,031, respectively. Changes in total employment amount to 145.5, 187.8 and 253.7 new jobs across 107 sectors. These effects are broken down into direct, indirect and induced economic impacts.

The majority of the indirect economic impacts quantified were found in agricultural sectors including cattle ranching, all other crop production, animal production, and greenhouse and nursery sectors. Significant effects are also found in the power generation, wholesale trade, truck transportation, architectural, and real estate sectors. The study provides a further breakdown of the direct, indirect, and induced effects on total output and employment by industry, across each policy scenario.

The results of this analysis serve only as a baseline representation of the potential benefits associated with a government cost-share program for irrigation technology. In reality, a government cost-share program would not involve wholesale adoption of the same type of irrigation system across each farm. Irrigation

technology adoption depends on several factors specific to each farm including different field characteristics and cropping patterns. The implementation of each scenario would also be staggered over several years and would not likely include all 3,750 farms within the basin. The impact analysis and results can be tailored to actual implementation. Total benefits can be discounted depending on the length of project implementation, and the cost of implementation can be changed to reflect the mix of irrigation technologies adopted at each farm.

In the second stage of analysis, the loss in total output associated with a reduction in irrigated acreage of 5, 10, and 15 percent amounted to $1,412,876, $2,825,753, and $4,238,631, respectively. These reductions include both direct and indirect impacts, as well as the induced effects of decreased household spending. The largest indirect impacts to output were seen in the agricultural related sectors as well as the power generation and supply, petroleum refineries, wholesale trade, transportation, credit, real estate, legal, accounting, and state and local government sectors. The induced effects were also relatively large in the wholesale and transportation sectors, however, the largest effects were seen in the consumer spending sectors such as residential housing, automobile manufacturing, food and beverage stores and services, real estate, telecommunications, insurance, and medical sectors.

Total employment in the agricultural sectors of interest were found to make up a very small percentage of total regional employment, thus, the employment impacts of a 5, 10 and 15% reduction in irrigated acreage in the Uncompahgre Valley were relatively small when taken in the context of the entire study region. The direct

employment losses across the grain, pasture, and alfalfa sectors amounted to a total of 25.6, 51.3, 76.9 jobs across each percent reduction of irrigated acreage scenario. In many of the rural towns in Delta and Montrose counties, where the loss of employment would occur, this could result a relatively large impact to the smaller sub-economy.

The costs associated with a land retirement program, or a long-term "no-action" scenario must be evaluated within the context of a proposed selenium remediation strategy. The second study in this series serves only as a baseline of potential impacts that may result as salt levels begin to increase beyond threshold levels in the Uncompahgre Valley. The impacts evaluated are those impacts associated only with a loss in production. These potential costs can be used by the analyst or planner to evaluate the tradeoffs between alternative selenium remediation strategies.

The potential economic impacts discussed in these first two studies represent only a portion of the total benefits of selenium remediation. Other benefits may include potential increased yields resulting from more efficient irrigation management, decreased labor costs, potential changes in cropping patterns, and decreased pumping costs. These factors stand to play an important role in the decision to adopt new technology and are in need of further research. Additionally, the justification for a government-supported selenium control program, must take into account the non-market benefits associated with decreased salt and selenium. Benefits to endangered species and the potential recreational benefits of increased flows, when accounted for, could also help to counter costs of implementation. The

implied positive external benefits associated with the mandatory adoption scenario further justify the funding of a government cost-share program.

The final paper in this series stems from the need to understand and evaluate the factors influencing water consumption in the state of Colorado. Specifically, this research develops an aggregate river basin demand model for the different water uses in the Gunnison River Basin.

The final Tobit model used performed relatively well. Factors found to significantly increase water consumption in the Gunnison River Basin include population, median household income, number of children under 5, number of people over the age of 25 with a college degree, number of people employed, population density, and total land area. Factors found to influence agricultural water use include number of irrigated acres, farm income, and number of cattle. The study was conducted at the macro-level across different water use sectors within each of the seven water districts within the Gunnison River Basin. Agricultural water use was found to be the dominant water use in each of the districts.

Model results were found to be generally consistent with economic theory. Water use was found to increase as population, income, and total land area of the water district increases. Agricultural water use was also shown to increase with the number of irrigated acres. The model also indicates that total water use decreases as density, annual precipitation, and the number of people employed increase. These relationships are also generally consistent with economic theory. For example, increases in population density mean that people are living closer together, requiring less water for landscaping and other outdoor uses. Increases in the number of people

employed may mean people use less water outside of the home. Precipitation was not found to significantly influence water use in the basin. The mean value for precipitation across all water districts is approximately 10.5 inches per year. This low rate of precipitation is classified as being close to dessert conditions, thus, small increases in the annual rate of precipitation will not affect irrigation water use, which constitutes the bulk of water use in the Gunnison River Basin.

The results of this study will ultimately be used for input into Aquarius, a state of the art computer model devoted to the temporal and spatial allocation of water among competing uses in a river basin. The model is driven by an economic efficiency operational criterion requiring the reallocation of stream flows until the net marginal return in all water uses is equal. Traditionally, water demand estimates used for regional planning purposes have been based on per-capita use, found by dividing total consumption or demand by the total population of the study area. This approach to water resources planning leaves much to be desired in terms of efficient water allocation and effective conservation policy because it does not identify the variables influencing water use in a given region.

The three papers discussed above represent a small part of the water related issues facing the Gunnison River basin. Overall, the Gunnison River basin is faced with many challenges related to current and future water use. Although there are other major river basins with more pressing issues, the Gunnison represents one of the state's most pristine watersheds, and therefore carries with it additional issues that must be considered in striking the balance between traditional water and future water use.